IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

Applicants:	Jonathan J. Wierer, Jr.; Michael R. Krames; Serge L. Rudaz		
Assignee:	Lumileds Lighting U.S. LLC		
Title:	Multi-Layer Highly Reflective Ohmic Contacts For Semiconductor Devices		
Serial No.:	09/469,652	Filing Date:	December 22, 1999
Examiner:	Jerome Jackson	Group Art Unit:	2815
Docket No.:	M-9197 US		

San Jose, California

Commissioner for Patents
P. O. Box 1450
Alexandria, VA 22313-1450

DECLARATION OF JONATHAN J. WIERER JR.

Dear Sir:

Jonathan J. Wierer Jr. declares as follows:

1. I received my Bachelor's, Master's, and Ph. D. degrees in Electrical Engineering from the University of Illinois in 1994, 1995, and 1999. I have worked in the field of semiconductor devices for 11 years. I am a co-inventor of the above-referenced patent application.

2. I have calculated the p-contact resistance for the device described in P.M. Mensz, P. Kellawon, R. van Roijen, P. Kozodoy, and S. Denbaars, *$In_xGa_{1-x}N/Al_yGa_{1-y}N$ violet light emitting diodes with reflective p-contacts for high singled sided light extraction*, Electronics Letters 20th November 1997 Vol. 33 No. 24, pp.2066-2068 (hereinafter "Mensz").

3. The attached Figure 1 gives a circuit diagram for a semiconductor light emitting diode, such as the device of Mensz. The circuit includes the resistance of the p-contact $R_{p\text{-contact}}$, the resistance of the p-type region $R_{p\text{-semiconductor}}$, the voltage necessary to

PATENT LAW GROUP LLP
2635 N. FIRST ST. SUITE 223
SAN JOSE, CA 95134
(408) 382-0480
FAX (408) 382-0481

pass current through the p-n junction V_{gap}, the resistance of the n-type region $R_{n\text{-}semiconductor}$, and the n-contact resistance $R_{n\text{-}contact}$. $R_{p\text{-}contact}$ may be rewritten in terms of the contact resistance $\rho_{p\text{-}contact}$, which is a function of the contact material, and the area of the p-contact $A_{p\text{-}contact}$, as given by equation (1):

$$R_{p-contact} = \frac{\rho_{p-contact}}{A_{p-contact}} \qquad (1).$$

4. The forward voltage V_f of the device at driving current I is given by equation (2):

$$V_f = \left(R_{p-contact} + R_{p-semiconductor} + R_{n-semiconductor} + R_{n-contact}\right)I + V_{gap} \qquad (2).$$

5. From equations 1 and 2, an expression for contact resistance $\rho_{p\text{-}contact}$ may be derived, as given by equation (3):

$$\rho_{p-contact} = \left\{\left(\left(\frac{V_f - V_{gap}}{I}\right) - \left(R_{p-semiconductor} + R_{n-contact} + R_{n-semiconductor}\right)\right)\right\}A_{p-contact} \qquad (3).$$

The values for V_f, I, and $A_{p\text{-}contact}$ are shown in paragraph 6, the value $R_{p\text{-}semiconductor}$ is calculated in paragraph 7, the value of $R_{n\text{-}contact}$ is calculated in paragraph 8, and the value of $R_{n\text{-}semiconductor}$ is calculated in paragraph 9, and the value of V_{gap} is calculated in paragraph 10. In paragraph 11, the values are substituted in equation 3 and the p-contact resistance is calculated. All values are calculated in favor of Mensz to give the lowest possible $\rho_{p\text{-}contact}$.

6. At page 2067, column 2, line 24 of Mensz, the value for current I is given as 20 mA, or 0.20 A. At page 2067, column 2, line 34 of Mensz, the value for forward voltage V_f is given as 5.0 ± 0.1 V. At page 2067, column 1, line 36 of Mensz, the value for area of the p-contact $A_{p\text{-}contact}$ is given as 300 x 300 μm^2, or 0.0009 cm^2.

7. The resistance $R_{p\text{-}semiconductor}$ is given by equation 4:

$$R_{p-semiconductor} = \frac{\rho_{p-sheet} L}{A_{p-contact}} \qquad (4)$$

PATENT LAW GROUP LLP
2635 N. FIRST ST. SUITE 223
SAN JOSE, CA 95134
(408) 382-0480
FAX (408) 382-0481

where $\rho_{p\text{-sheet}}$ is the sheet resistance of the p-type semiconductor, L is the thickness of the p-type semiconductor, and $A_{p\text{-contact}}$ is the area of the p-contact. At page 2067, column 1, lines 29-33, Mensz recites several p-type layers, including: "p-type GaN doped with Magnesium at $1 \times 10^{19}\text{cm}^{-3}$ . . . Mg doped layers of 150Å thick p-$Al_{0.10}Ga_{0.90}N$ doped at $1 \times 10^{19}\text{cm}^{-3}$, 600Å thick graded composition p-$Al_yGa_{1-y}N$, from y = 0.10 to y = 0.0, doped at $5 \times 10^{19}\text{cm}^{-3}$, and 2000Å thick p^+-GaN doped at $1 \times 10^{20}\text{cm}^{-3}$ . . . ." Adding all of these layers gives a total p-layer thickness of 2750Å or 0.0000275 cm. The sheet resistance $\rho_{p\text{-sheet}}$ of GaN is reported by S. Nakamura, Semiconductors and Semimetals, Vol. 48, 391 (1997) to be between 2 and 8 Ω-cm. Since the higher value of sheet resistance $\rho_{p\text{-sheet}}$ gives a smaller value for contact GM) resistance $\rho_{p\text{-contact}}$, the value of 8 Ω-cm is used. As described above in paragraph ~~8~~ 6, the area of the p-contact $A_{p\text{-contact}}$ is 0.0009 cm^2. Substituting these values in equation 4 as illustrated below gives a value of $R_{p\text{-semiconductor}}$ of 0.18 Ω.

$$R_{p-semiconductor} = \frac{(8\Omega cm)(0.0000275cm)}{0.0009cm^2} = 0.24\Omega \qquad (4).$$

8. The resistance $R_{n\text{-contact}}$ is given by equation 5:

$$R_{n-contact} = \frac{\rho_{n-contact}}{A_{n-contact}} \qquad (5)$$

where $\rho_{n\text{-contact}}$ is the n-contact resistance and $A_{n\text{-contact}}$ is the area of the n-contact. Mensz states at page 2067, column 1, lines 39 and 40 that the n-contact is Ti/Al. The n-contact resistance of Ti/Al on n-type GaN is reported by Lin et al., Low resistance ohmic contacts on wide band-gap GaN, Appl Phys. Lett. 64 (8) (1994) to be between 3×10^{-3} Ω-cm^2 for a small contact area and 8×10^{-6} Ω-cm^2 for a large contact area. Without knowing the exact quality of Mensz's n-contact, 3×10^{-3} Ω-cm^2 is used for the n-contact resistance. This gives the highest $R_{n\text{-contact}}$ (and hence the lowest $\rho_{p\text{-contact}}$). The contact area is assumed to be the 100 x 100 μm^2 or 0.01 x 0.01 cm^2. This is the smallest contact area that can be probed and wire-bonded, and was chosen because using a small contact area increases the size of the $R_{n\text{-contact}}$ term, which

PATENT LAW GROUP LLP
2635 N. FIRST ST.
SUITE 223
SAN JOSE, CA 95134
(408) 382-0480
FAX (408) 382-0481

decreases the $\rho_{p\text{-contact}}$. Substituting the values for n-contact resistance $\rho_{n\text{-contact}}$ and n-contact area $A_{n\text{-contact}}$ in equation 5 as illustrated below gives a value for $R_{n\text{-contact}}$ of 30 Ω.

$$R_{n-contact} = \frac{3 \times 10^{-3}\,\Omega cm^2}{(0.01cm)(0.01cm)} = 30\Omega \quad (5).$$

9. The resistance $R_{n\text{-semiconductor}}$ is given by equation 6:

$$R_{n-semiconductor} = \frac{L}{A_{n-semiconductor}\, q n \mu} \quad (6)$$

where L is the length current must spread in the n-type layer, $A_{n\text{-semiconductor}}$ is the cross sectional area through which current must spread, q is the electron charge, n is the electron concentration in the n-type layer, and μ is the mobility of the electrons in the n-type layer. For a square 300 x 300 μm^2 p-contact, the size recited by Mensz at page 2067, column 1, line 36, the average current spreading length L is assumed to be 150 μm, or 0.015 cm. The cross-sectional area $A_{n\text{-semiconductor}}$ is 300 μm (the length of one side of the p-contact) times the thickness of n-type material through which current must spread. At page 2067, column 1, lines 22-26, Mensz teaches three n-type layers: "2.5 μm of n-type GaN doped with Si at 2 x 10^{18} cm^{-3} donor concentration . . . . a 450Å thick graded composition layer of n-$Al_yGa_{1-y}N$ from y = 0 to y = 0.08, and a 150 Å thick n-$Al_{0.08}Ga_{0.92}N$ layer . . . both doped with Si at 1 x 10^{18} cm^{-3}." Since the 450Å thick graded layer and the 150 Å thick AlGaN layer add only negligibly to the resistance, the thickness of n-type material through which current must spread is assumed to be 2.5 μm, or 0.00025 cm. The electron charge q is 1.6 x 10^{-19} C. Mensz recites a donor or electron concentration n of 2 x 10^{18} cm^{-3} in the above-quoted passage. The electron mobility in n-GaN is reported by Götz et al., Activation energies of Si donors in GaN, Appl. Phys. Lett. 68 (22) (1996) to be 300 cm^2/Vs. Substituting these values in equation 6 as illustrated below gives a value of $R_{n\text{-semiconductor}}$ of 20.8 Ω.

$$R_{n-semiconductor} = \frac{0.015cm}{(0.03cm)(0.00025cm)(1.6x10^{-19}C)(2x10^{18}cm^{-3})(300cm^2/Vs)} = 20.8\Omega \quad (6).$$

PATENT LAW GROUP LLP
2635 N. FIRST ST.
SUITE 223
SAN JOSE, CA 95134
(408) 382-0480
FAX (408) 382-0481

10. The voltage V_{gap} is given by equation 7:

$$V_{gap} = \frac{hc}{\lambda} \tag{7}$$

where h is Planck's constant, 4.14 x 10^{-15} V.s, c is the speed of light in a vacuum, 3 x 10^{8} m/s, and λ is the wavelength of light, stated at page 2067, column 2, line 12 to be 412 nm or 412 x 10^{-9} m. Substituting these values in equation 7 as illustrated below gives a V_{gap} of 3V.

$$V_{gap} = \frac{(4.14x10^{-15}V \cdot s)(3x10^{8}m/s)}{(412x10^{-9}m)} = 3V \qquad (7).$$

11. The values in paragraphs 6-10 are substituted in equation 3 as illustrated below:

$$\rho_{p-contact} = \left(\left(\frac{5V-3V}{0.02A}\right) - (0.24\Omega + 30\Omega + 20.8\Omega)\right)0.0009cm^2 = 0.044\Omega\text{-cm}^2 \qquad (3).$$

Since all the assumptions made in the above calculations favor arriving at the lowest possible $\rho_{p\text{-contact}}$, I believe 0.044 Ω-cm^2 is the lowest possible $\rho_{p\text{-contact}}$ for Mensz's device.

I declare that all statements made herein of my own knowledge are true and that all statements made on information and belief are believed to be true; and further that these statements were made with the knowledge that willful false statements and the like so made are punishable by fine or imprisonment, or both, under section 1001 of Title 18 of the United States Code and that such willful false statements may jeopardize the validity of the above-referenced application or any patent issued therefrom.

Signed: Jonathan J. Wierer Jr.

Date: 30 June 2005

PATENT LAW GROUP LLP
2635 N. FIRST ST.
SUITE 223
SAN JOSE, CA 95134
(408) 382-0480
FAX (408) 382-0481